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Generation IV Roadmap

Crosscutting Energy Products R&D Scope Report

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ABSTRACT

The Generation IV Roadmap process is focusing on the development of reactor systems that would be ready for commercial deployment by the year 2030. In addition to the production of electricity, Generation IV systems may serve other missions. Among these are consumption of waste from the nuclear fuel cycle, production of fissile materials, and the generation of other energy products. Alternative energy products include hydrogen, desalination of water (particularly for residential, agricultural and industrial uses), high temperature process heat, other heat applications, and district heating. The greatest potential of these options appears to be the generation of hydrogen.

EXECUTIVE SUMMARY

The Generation IV Roadmap process is focusing on the development of reactor systems that would be ready for commercial deployment by the year 2030. In addition to the production of electricity, Generation IV systems may serve other missions. Among these are consumption of waste from the nuclear fuel cycle, production of fissile materials, and the generation of other energy products. Alternative energy products include hydrogen, desalination of water for residential, agricultural and industrial uses, high temperature process heat, other heat applications, and district heating.

This report examines the mission of these other energy products. Particular focus is given to hydrogen, the state of the technology readiness, and the requirements for Generation IV systems to serve this mission. Ten crosscut areas for research and development relevant to the energy products mission are identified and discussed. These include:

- Temperature needs for various processes
- Size of plants to serve the energy products missions
- Product quality and prevention of contamination of a consumer product with tritium
- Integrated safety of a nuclear heat source with an industrial process such as hydrogen production
- Inherent safety of Generation IV systems as perceived by industrial end users
- Coupled plant dynamics and the requirements on a nuclear heat source to match the loads, load cycles and reactor cycles imposed by other processes than electricity generation
- Intermediate heat transfer loops and the need to provide the heat from a Generation IV reactor to match industrial user requirements
- Modular systems and the definition of modularity and shared facilities if reactors are distributed across and industrial site
- Role of the Brayton Cycle and co-generation
- Observations on providing nuclear heat for aluminum production and other industrial uses.

The report also examines R&D needs in the areas of energy products themselves and advanced energy conversion for Generation IV systems. Regarding thermochemical cracking of water to produce hydrogen, seven activities are identified. The focus is on the two most promising thermochemical processes involving iodine-sulfur and calcium-bromine. The areas include:

- Materials selection for temperature, corrosion and lifetime service needs
- Thermochemical properties and measurements, and the development of needed data bases
- Determination of rate constants for the particular chemical processes
- Development of process flowsheets and thermodynamic optimization of the integrated processes
- Development of bench scale tests
- Construction and operation of a small-scale prototype.

For the calcium-bromine process, there is an additional need to select the support structure and materials of the calcium material in the process.

In coming decades, given looming global shortages, water may emerge as an equally important product for Generation IV systems. For desalination, four R&D activities are identified:

- Development of relevant models and adaptation of the IAEA model for nuclear desalination to Generation IV systems
- Monitor R&D progress in the fields of optimized reverse osmosis and multi-effects distillation for use with Generation IV concepts
- In the field of multi-stage flash distillation processes, track developments on heat exchangers, crud control and brine disposition
- Evaluate commercial opportunities for coupling to product extraction from brine of materials such as uranium and other products with market value.

Generation IV concepts also provides opportunities to utilize new energy conversion approaches that have not previously been associated with nuclear power. R&D needs for two of these are discussed. For the Supercritical CO_2 Brayton Cycle, these include

- Thermodynamic optimization of the cycle with high temperature nuclear heat
- Consideration materials requirements including selection of materials for heat exchangers, recuperators and turbines and turbine blades
- Performance of small scale testing of supercritical CO_2 turbines and the recuperators for these cycles.

Finally, in conjunction with the Supercritical Steam Rankine Cycle for the SCWR concept developed by the Water-Cooled Technical Working Group, additional R&D needs for the energy conversion include:

- Reviews of fossil plant experience in this field and evaluation of technical relevance to the SCWR
- Monitoring of work in other national programs, especially the BREST reactor in Russia
- Economic comparisons and the development of robust economic models for the SCWR.

In conclusion, the opportunities for other energy products from nuclear systems appear to be immense. Generation IV concepts meet a wide range of temperature requirements which allow nuclear to be considered for a variety of other energy missions. Nuclear already provides, by far, the largest fraction of non-CO_2 emitting primary energy, and the importance of this attribute is only expected to grow over the years and decades to come.

Generation IV Roadmap
Crosscutting Energy Products R&D Scope Report

1. INTRODUCTION

Electricity is “a high value-added” product that drives economic vitality, supports growth in productivity, and increases the quality of life for society. By the beginning of the 20^{th} century, electricity was successful in displacing coal, candles, whale oil and other means to distribute energy because it was easily transportable, clean, and best met requirements for a tremendous variety of end-use applications. Customers and consumers found that electricity best provided what they sought in a clean, flexible, convenient, and reliable form of energy.

Fifty years of experience with nuclear power has resulted in an electrical energy source having operation and maintenance (O&M) costs that are competitive with virtually all other means of electricity generation. Due to increased efficiencies resulting in shorter refueling and maintenance periods, reductions in unanticipated outages, and power-up rates of existing plants, O&M costs for nuclear are lower than for coal, natural gas, oil, and alternative sources. Among the significant contributors to electricity production, only hydroelectric plants have lower O&M costs. In addition, among the “non-emitting” sources that produce no CO_2, nuclear power generates almost three times as much electricity as hydro, wind, and a solar sources combined (see Figure 1), and due to its high energy density, has dramatically smaller land impact for the same power output.

However, to remain as a major component of the energy mix, the nuclear industry must demonstrate that plants can be built and commissioned in a reasonable amount of time at a competitive price. The new approach by the Nuclear Regulatory Commission in 10CFR52 to certify designs and perform separate site reviews, is meant to create conditions for timely construction and licensing to operate. The next major step is to verify that this approach can result in the building of a plant without becoming enmeshed in regulatory challenges and delay. If successful, this new construction will resolve a major uncertainty about future contributions from nuclear power.

Nuclear Power Contributes to Cleaner Air

- Displaces other polluting forms of electricity generation
- Emission-free generating sources supply almost 30% of America's electricity
- Nuclear energy provides the greatest share of clean energy – over 70% - avoiding about 175 MMTC each year

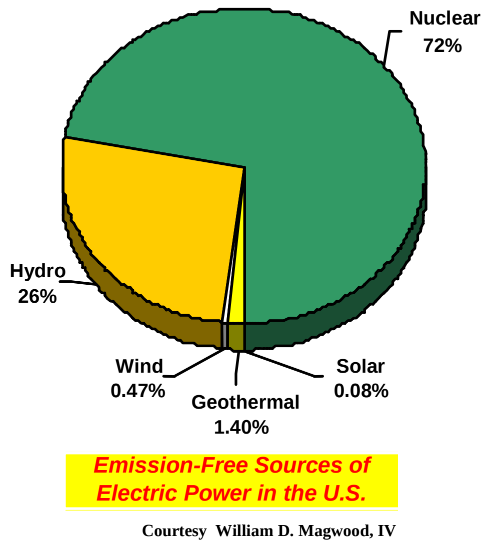

Figure 1. Current fractions of non-CO_2 emitting energy sources.

The Generation IV concepts increase the opportunities for contributions from nuclear power. Reaching commercial viability in 2030, Generation IV systems will enable nuclear to play a major role as a primary heat source for processes and products in addition to generating electricity. This report examines these other potential energy products.

2. OTHER ENERGY PRODUCTS

In the past, nuclear energy has served only as a generator of electricity. However, in the decades to come, nuclear may be called upon to play a significantly expanded role in the energy sector. Four applications are examined in this report beyond electricity. These roles are: hydrogen, high temperature process heat for other industrial applications, desalination to produce fresh water, and district heating. It should also be noted that nuclear has proven itself as a means for naval propulsion, albeit primarily for military applications. However, this approach may yet prove feasible and attractive over the longer term for commercial marine use.

Figure 2 shows the breadth of nuclear applications. If the markets develop and the economics evolve in such as way to make nuclear a credible and viable supplier of energy in these areas, the role for nuclear in the total energy mix could expand dramatically. It is also noted that a methodology is needed to consistently evaluate the economic potential for Generation IV systems to serve other energy products. Such a methodology is discussed in Appendix A.

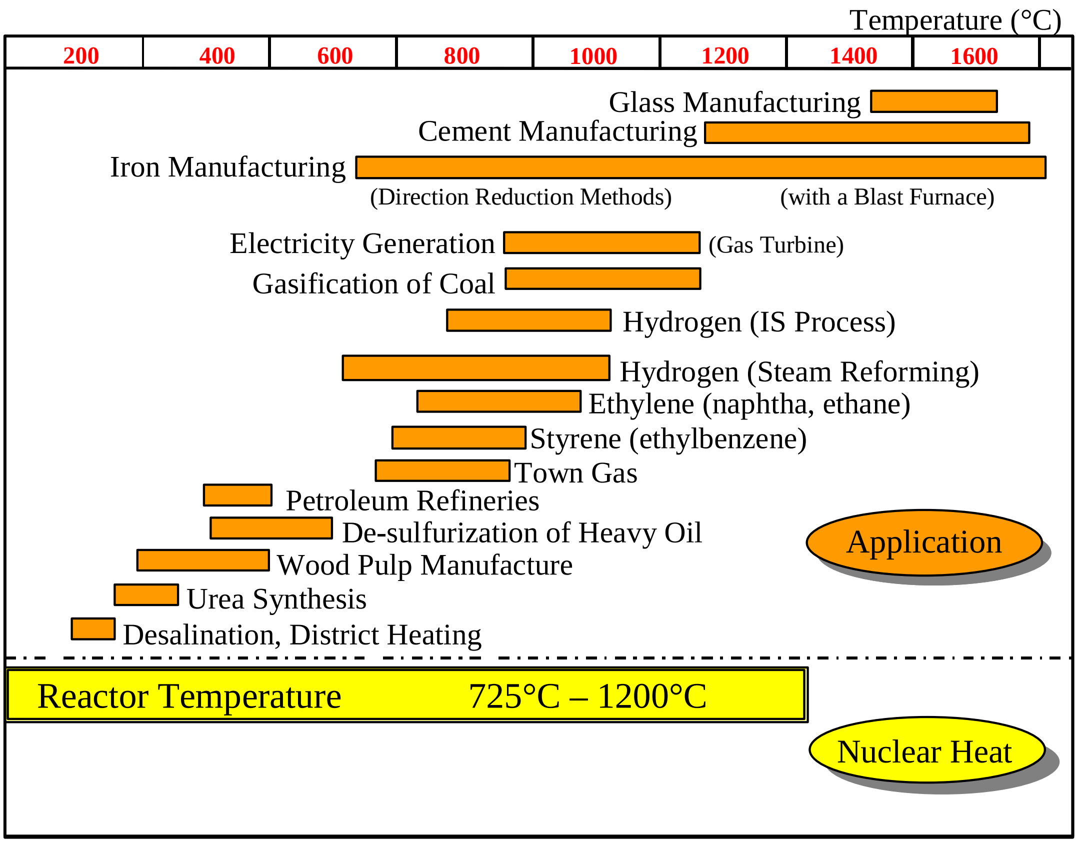

Figure 2. Potential uses of nuclear heat from Generation IV Systems.

2.1 Hydrogen

Attention is being given to the role of hydrogen in the future energy economy. It is important to note that hydrogen is not an energy source. Instead, like electricity, hydrogen would serve as a useful means to transmit energy from a primary source and apply it for an end use. Electricity and hydrogen serve energy carriers or energy “currencies,” and this parallel means of delivery is termed “hydricity.”

In actuality, a major hydrogen economy already exists. Significant amounts of hydrogen are currently produced for the manufacture of anhydrous ammonia for fertilizer. Hydrogen also plays a large, and growing role, in the refining of petroleum products. Increased use of hydrogen is taking place because the reserves of high quality light sweet crude oils are declining and the available crude stocks are becoming progressively heavier. These heavier crude oils require greater amounts of hydrogen to increase the hydrogen-to-carbon ratio. The higher hydrogen-to-carbon ratio is needed to produce cleaner burning end-point fuels and to reduce toxicity through removal of sulfur. Refineries along the Texas Gulf Coast already exchange hydrogen as a commodity to meet production needs. The longest hydrogen pipeline in world, extending approximately 200 miles between Houston and Beaumont, Texas, serves this purpose. A second major hydrogen pipeline is serving a similar role connecting facilities at the southern end of Lake Michigan in northern Indiana and Illinois. In the United States, assuming 50% efficiency, hydrogen production will soon require the equivalent of the output of all 103 existing nuclear power plants. In addition, hydrogen demand is expected to grow at a rate of 4–10% annually.

The significant growth potential for hydrogen lies especially in two areas: in the transportation sector and as a distributed among electrical energy source through the use of fuel cells. In developed countries, primary energy is approximately evenly distributed among electricity generation, transportation, and industrial and residential uses. If, or when, hydrogen begins to be used for transportation, the demand for and the capability to produce hydrogen will accelerate rapidly. Currently hydrogen is primarily produced through steam reforming of methane. This has two implications. The source material is natural gas, and as a result represents a draw on a valuable resource. In addition, a by-product of the hydrogen production process by methane steam reforming is CO_2, a gas contributing to global climate change.

2.2 The Hydrogen Future

The future for hydrogen, and the potential for nuclear generated hydrogen, will be driven by three major factors: production rates of oil and natural gas, societal and governmental decisions about global climate change gases and CO_2 emissions, and the economics of hydrogen production and transmission.

2.2.1 Oil and Gas Production

Since the beginning of the industrial revolution in the mid-19th century, the development of technology to meet societal demands has been largely fueled by the availability of cheap fossil fuels. The liquid forms, oil and gas, have been especially critical because of the relative ease of recovery and their high utility for use in industrial and transportation applications. However, it is very likely that a look back from some point far in the future will reveal that the century between 1950 and 2050 will prove to be an anomalous period in world history. During this time the growing global appetite for oil and gas was served at historically low prices. However, today’s new finds are often in remote locations or in deep water, and this anomalous period is destined, at some time, to come to an end. Projections reported by the U.S. DOE Energy Information Agency suggest that the peak in world oil production, as shown in Figure 3, could occur as soon as 2010. Although this may be premature in view of continuing discoveries, when production peaks and begins to decline, and production costs increase, the impact on the world’s economies will be enormous. These costs will result in growing price instability and drive critical issues of energy security. These concerns are major factors even now, while gas and oil are relatively abundant.

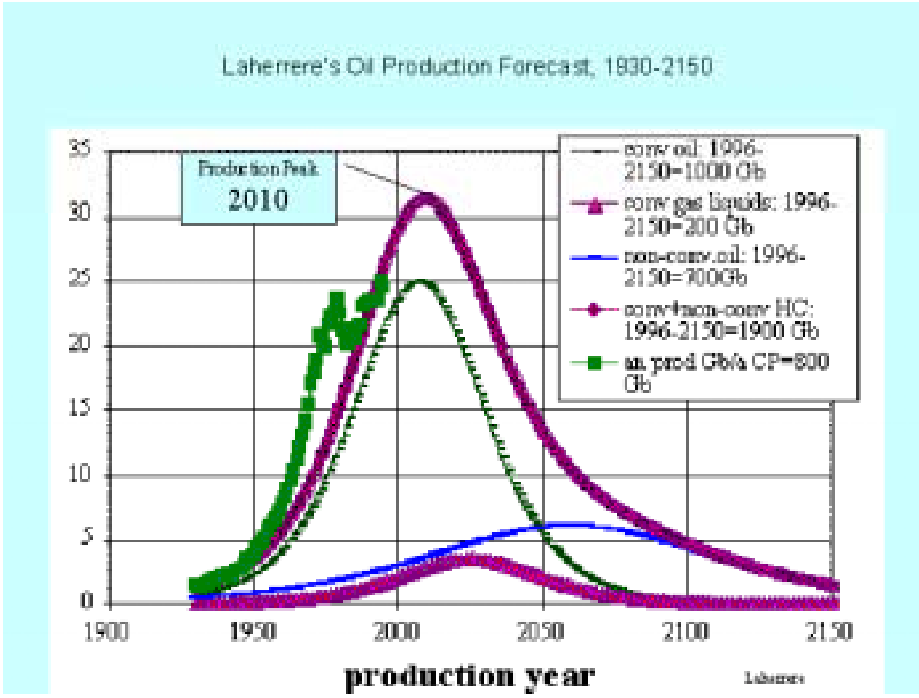

Figure 3. Projection of global oil and gas production.

By comparison, the impact of future instabilities will be considerably exacerbated. Most at risk are those countries with little or no indigenous energy supplies and limited capital. These areas will very likely be the less developed countries and the economic burdens will be daunting. Substitution of new forms of energy for oil in the transportation sector and natural gas in the heating, manufacturing, and electricity sector will immediately become a top global priority.

2.2.2 CO_2 and Global Climate Change

In roughly the same time frame, before 2050, a decision will have to be made about CO_2 emissions and climate change gases. Current atmospheric concentrations are approaching 370 ppm. This figure is higher by 45 ppm than any point during the last 450,000 years, which encompassed four ice ages and four periods of global warming, as shown in Figure 4. In addition, without dramatic shifts to non-CO_2 sources, projections of CO_2 could reach over 500 ppm in a few decades and 800 ppm by mid-century. The implications of these concentrations are unknown but could very likely be severe.

As evidence becomes more compelling that CO_2 is a contributor to global climate change, individual governments and world society as a whole will decide how this is to be approached. Presumably many strategies will be available. To influence a course of action, governments normally have three policy options—prohibition, disincentives through means such as taxes or fines, and incentives to reduce emissions of greenhouse gases. Historically, prohibition has proven to be spectacularly unsuccessful, and this would presumably again be the case, should governments try to outlaw CO_2 -producing activities.

The second course involving a carbon tax is immensely controversial and may be politically challenging. However, it is noted that governments have taken action through the use of fines to significantly reduce the emissions of air pollutants such as sulfur dioxide, nitrous and nitric oxide, and in another context, chlorofluorocarbons, when such reductions have been judged to be in the national interest. Society seems to have accepted this, and consumers are paying the costs of these actions. If a similar consensus is reached over CO_2, these strategies presumably can be implemented in the future. Such approaches would be most successful for large, point source emitters, especially power plants. Trying to influence small, distributed sources such as automobiles, trucks, and buses would be more challenging; although again, there is precedent in requiring catalytic converters and monitoring the performance of these measures through regular inspection.

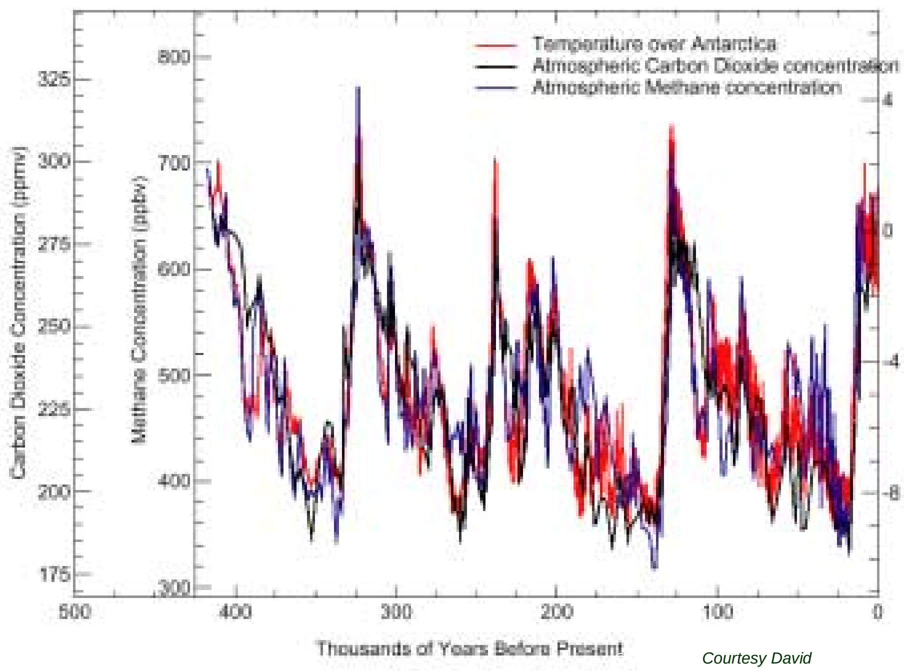

Figure 4. CO_2 concentrations and temperature over Antarctica.

The third path of introducing incentives such as tax breaks for the purchase of vehicles with reduced CO_2 emissions may be used as well. However, in general, these incentives tend to have limited appeal unless there is a real economic benefit to the consumer. Tax breaks for weatherization of homes or installation of solar collectors have had limited success unless homeowners believe they will see real financial returns on a timely basis.

The debate and move towards solutions regarding global climate change and CO_2 is only in the initial stages. No consensus, much less agreement, has yet emerged on how to respond. The Kyoto Accords call for a roll back of greenhouse gas emissions by 2010 to levels below those of 1990. This achievement will prove to be a challenging task since emission levels have continued to rise since 1990 and the time to achieve reductions is growing shorter. The Kyoto signatories have begun implementation by increasing efficiencies and greater utilization of lower or nonemitting energy sources. However, nuclear power is often not regarded as a nonemitting source. The financial impact of implementing the Kyoto Accords is probably still to be fully understood (as in fact is true for the entire global financial impact of climate warming). Alternatively, in foregoing the Kyoto Treaty, the Bush Administration has announced intentions to develop hydrogen vehicles through the FreedomCAR initiative, to be carried out on a time scale longer than first implementation of the Kyoto Accords.

2.2.3 Economics of Hydrogen

The ultimate test for large-scale penetration by hydrogen will be determined by the economics of production and end use. Consumer perceptions regarding availability and convenience of use will be important as well. On the production side, three technologies are available. To date the most prevalent method of hydrogen production is steam reforming of methane. This process uses natural gas as a feedstock and produces CO_2 as a byproduct. Steam reforming of methane is used extensively by refineries. Nuclear driven steam reforming may well serve as a bridge to direct water splitting, and may also allow opportunities for much nearer term use of nuclear power for hydrogen production. In addition, research is underway using membrane techniques that can recirculate reaction product gases and further reduce the CO_2 from steam reforming. Nuclear-assisted steam reforming of methane could constitute a strategy for a successful continuum towards other CO_2-free production approaches.

Alternatively, electrolysis of water also yields hydrogen with no CO_2. Electrolytic processes have historically tended to have low efficiencies, but this is a very active field of research with improvements occurring regularly. Currently efficiencies are in the range of 60–80% and the may reach 90%. Coupled with high temperature reactor concepts with improved efficiencies, optimized hot electrolysis has the potential to be a significant contributor to hydrogen generation. In addition, electrolyzers can be very attractive to serve as distributed production sites for hydrogen.

More recently attention is being given to thermochemical production techniques. Processes such as sulfur-iodine or calcium-bromine show promise. Generally these processes tend to require higher temperatures, with the sulfur-iodine process needing 900–1,000°C. Higher temperatures may be desirable since reaction rates and efficiencies usually scale proportionally. However, research results suggest that lower temperatures down to 725°C may be possible for the calcium-bromine process. Both processes still have to be demonstrated on an industrial scale. However, efficiencies of the order of 50% are envisioned which should make thermochemical processes attractive.

A final note on production economics is in order. Current production of hydrogen through steam reforming is being done primarily at refineries. This process requires significant investment in facilities. In addition, embedded in the costs for producing hydrogen by this route is the cost of the feedstock. In fact, the cost of the natural gas makes up about 50% of the cost of the product. This is not atypical for other processes using natural gas such as electricity production. However, within the framework of generating hydrogen for blending down of heavy crudes, the economics are such that refineries find the investment and costs are worthwhile to produce a marketable high grade gasoline. So this use of hydrogen in the energy sector is already economically viable and sufficiently attractive to companies to warrant the investment for the production and handling of hydrogen. For the other production routes involving electrolysis or thermochemical processes, the feedstock, water, will be considerably less costly than natural gas so with continued research and development, facilities that are competitive for hydrogen production should be attainable. On the end-use side, the economics will be largely determined by improvements in fuel cells. This is a field with significant ongoing activity. At the March, 2002 meeting of the American Institute of Chemical Engineers, approximately 100 papers were presented on fuel cell research. Several automakers are moving towards demonstrations of vehicles powered by fuel cells. Toyota has a hybrid model, the Prius, on the market and Ford will offer a fuel cell powered vehicle in 2004. In addition, significant use of fuel cells for distributed electricity production is already occurring, although currently these fuel cells are generally not powered by hydrogen. But it indicates important trends towards the acceptance and use of fuel cells. As fuel cells using hydrogen become gain more "market penetration," they also will presumably reduce in cost through production experience and gain greater use and form an alternative to natural gas powered fuel cells. Extensive active research is underway in promising technologies.

2.3 The Synergism of Electricity and Hydrogen and Water

For future applications, electricity and hydrogen form an “elegant” system for transferring energy from primary sources to end uses (energy currencies) with the possibility of intermediate storage. Energy in the forms of electricity and hydrogen is interchangeable, although conversion losses obviously occur. Electricity and hydrogen are also complementary to each other as energy currencies. Electricity does some things extremely well and hydrogen does not. The converse is also true. For example, electricity is readily converted to do work through motors while at the same time powering a global information infrastructure. But it must be produced at the same time that it is to be used. Electricity is generally produced by large, or relatively large, central station plants, although alternative technologies may make distributed production of electricity more feasible. However, no matter what means of production is used, storage of electrical energy is generally costly and not particularly efficient. Much effort has gone into battery technology, superconducting magnets, fly wheels, pumped hydro and other means of “storing” electricity with no clear cost effective winner. Conversely, hydrogen offers flexibility in that it can be stored, although with some challenges. However, multiple economic approaches for storing hydrogen may become more feasible. Hydrogen, particularly through electrolysis, is also amenable to distributed production. When these complementary characteristics of electricity and hydrogen are coupled with a variety of production strategies, this resulting system is incredibly flexible on a macroscale and provides a large number of “degrees of freedom” in designing a national energy infrastructure. For example, current electricity production is normally defined as base load or peaking. A base load plant can have high capital costs but lower fuel and operating costs making nuclear ideal for this role. Alternatively, peaking plants, because they operate intermittently, are characterized by lower capital costs and by higher fuel costs. Natural gas peaking plants are prime examples. However, with hydricity, the distinctions between base load and peaking production will disappear and the overall system can be optimized using different criteria. The output from a large electricity generating plant may go towards meeting the entire demand during peak periods, but the electrical output can be directed towards generating hydrogen during off-peak periods. Likewise, hydrogen is a potentially attractive form in which to store energy since the hydrogen output might be distributed or alternatively used to meet peak demand through fuel cells. Thermochemical production plants likewise might produce hydrogen for peaking use or for distribution. Experience has demonstrated that hydrogen can be transported by pipeline. However, energy transmission can be done with electricity and the conversion to hydrogen done at widely distributed local sites through electrolysis. Hydrogen can also be stored in high-pressure composite tanks or as a cryogenic liquid. However, other mechanisms for hydrogen storage are under development that may prove to be more favorable. In these schemes, the hydrogen is recovered as needed, on board a vehicle. Finally, combustion of hydrogen is also feasible and may ultimately form an alternative for transportation modes such as air travel.

In certain areas, there are other advantages of the nuclear generated electricity/hydrogen duality. Currently in petroleum refining, costs of gasoline are impacted by a variety of factors. These can include foreign production schedules, changes in shipping schedule, spot market prices, weather, international events and many other influences. With hydricity, many of these uncertainties are eliminated. The opportunities will be available to draw upon a stable, reliable indigenous energy supply unaffected by the myriad of factors that currently impact energy prices. Hydrogen and electricity produced from nuclear is an energy paradigm that means economic stability, eliminates massive balance-of-payment deficits, and offers complete security from international instability.

2.4 Desalination

Water enters strongly into the picture of future energy products as well. In five decades, with a population approaching 10 billion, availability of potable water may well become the overriding issue that drives global relationships and transcends all other international factors. Already in many parts of the world and in major metropolitan areas, water issues are determining the potential growth and economic development of large regions. These challenges are not confined to developing countries. Even in the U.S., especially in Texas and the Southwest, the availability of water is the cause of rising tensions among neighboring municipalities, states and nations.

Even more important may become the allocation of water to meet the needs of residential communities and industries that are competitors to agriculture. Cities such as Los Angeles, San Antonio, Laredo, Phoenix and Las Vegas may not be able to sustain growth without additional large supplies of water. As an example, the Texas legislature regularly grapples with water issues trying to allocate a fixed supply to meet a variety of growing demands, and water is a factor in relations between the U.S and Mexico.

The need to provide potable water to the expanding population and growing cities in arid regions is a strong emerging application for nuclear power. The removal of salt and other impurities from seawater or brackish waters is generally done through one of two basic approaches: distillation and processing through membranes. Multi-Stage Flash Desalination is used in large applications such as in Saudi Arabia to produce large amounts of fresh water. The heat source is generally surplus natural gas. Other methods include Multiple Effect Distillation (MED) and Reverse Osmosis (RO). MED requires a heat input at 80–120°C, and through a series of heat exchangers, uses that heat in five to 12 stages to vaporize and condense water at progressively lower pressures. Electrical input is required only for pumps. In the RO method, water is forced through specialized membranes that selectively remove the salt and other impurities. The primary input to the RO process is electricity to operate the pumps. In addition, through optimization, the efficiency of the RO process can be improved by preheating the seawater to about 80°C.

Recent developments in RO membranes have substantially increased performance, efficiencies, durability, and ability to withstand harsh operating conditions. Economic analyses have recently shown that the RO process is more economical than the MED process ($0.45 /m^3 for RO, $0.50 / m^3 for MED for large plants). Nevertheless, the MED process is a simpler technology that may find niche markets and locations.

The appropriate desalination method will be determined by energy requirements, energy availability, purity requirements, and the particular markets with nuclear driven desalination could be used. As in other applications, nuclear heat and nuclear electricity may become increasingly attractive due to the replacement of other more expensive fuels and to the absence of CO_2 emissions.

2.5 High Temperature Process Heat

As noted above, there are a variety of applications for Generation IV systems for industrial processes. Many of these are shown in Figure 2. These can range from temperature requirements from approximately 300°C to almost 1,600°C. In addition to hydrogen production previously discussed, these applications include

- Urea synthesis
- Wood pulp manufacture
- Desulfurization of heavy oil
- Petroleum refining
- Production of town gas

- Manufacture of styrene, ethylbenzene, ethylene, naphtha, and ethane
- Gasification of coal
- Iron, cement and glass manufacturing.

Some of these processes are discussed in more detail in Appendix B.

The use of nuclear heat for these many applications is attractive for several reasons. It reduces the consumption of the fossil resource, which itself will ultimately prove to be more valuable for other applications than generating heat. This is especially true even now for natural gas, which serves as the feedstock for the global plastics industry. In addition, substituting nuclear heat sources for fossil sources would have a significant impact in reducing CO_2 emissions, as well as contributing to improved air quality in major cities. In the U.S. alone, increasing numbers of metropolitan areas are in danger of falling into "nonattainment" status with respect to local air quality. Were it possible to use nuclear sources in industrial locations now, major strides could be made in improving regional air quality in large metropolitan/industrial areas around the world. The challenge for Generation IV will be to develop systems that can be used and accepted in or near population centers.

2.6 District Heating

As already noted, nuclear sources may make contributions as a heat source for district heating schemes. The temperatures required are typically low, of the order of 80°C. It is worth noting that a number of major cities and industrial areas, especially in Eastern Europe, Russia, and the Former Soviet Union republics, already have the infrastructure in place for extensive use of district heating. Fossil sources now supply the heat for these networks. For nuclear to become competitive, the heat would have to be supplied at similar or lower prices, or meet new environmental limits such as offsetting CO_2 emitting sources.

One district heating network specifically based on nuclear heat has been built. This is located in Canton Aargau in the north central region of Switzerland. In the early 1980's, the infrastructure was built to deliver heat energy from the Beznau Nuclear Power Station located near Döttingen, Switzerland. The Beznau plant consists of two Westinghouse 350 MW_e PWRs built and commissioned in 1972. The Refuna network provides district heating to eleven communities in the vicinity of Beznau. A primary distribution network totaling 31 km was constructed connecting to an additional 97 km of secondary piping. A total of 2,273 users are served. These include homes, apartment buildings, shops, and industrial plants. The network has a capacity of 80 MW_{th} of heat energy.

The primary goal of the Refuna network is to displace heating oil. To this end, annually the network replaces 12,740 tonnes of heating oil and reduces CO_2 emissions by 44,410 tonnes. Cost for the energy is estimated to be approximately $0.04/$kWh_{th}$.

2.7 Energy Product Missions for Generation IV Systems

Generation IV systems are targeted for commercial availability by 2030. In this century, the true impact of Generation IV systems will be made in the ensuing 70 years after 2030, and beyond, as the world moves away from the period of inexpensive oil and gas and towards non-emitting forms for sources, transmission, and use of energy. In addition, Generation IV systems contribute to this new energy strategy by operating at higher temperatures yielding increased efficiencies in electrical generation, thermochemical processes or for industrial process heat applications. This reduces the amount of waste produced on a basis of unit of energy generated, and many of the Generation IV systems will further reduce waste by recycle or in situ burning.

Hydrogen and hydricity represent a major change, but are well within the scope of feasibility and economic viability. It is possible that these changes may in fact begin in the near term. As the developed nations grapple with these new directions and evolve policy to respond, it is critical that the technology options are available for implementation. In addition, hydrogen offers a means by which nuclear can contribute more significantly to electricity generation and distribution. In fact, through hydrogen, nuclear will become a key factor in the transportation sector as well. Hydrogen, high temperature industrial process heat, district heating, and desalination represent the means through which nuclear will provide nonelectric products, which constitute the remaining two-thirds of the energy markets.

3. EVALUATION OF THE SUITABILITY OF GENERATION IV SYSTEMS FOR OTHER ENERGY MISSIONS

In the following sections, the concepts from each of the four technical working groups are examined for the energy products missions beyond electricity. A table in a common format lists the primary characteristics, and the potential nonelectrical roles each can fill.

3.1 Evaluation of Water-Cooled Reactor Concepts for Other Energy Missions

The three concepts advanced by the Water-Cooled Reactor Technical Working Group (TWG1) are the Super Critical Water Reactor (SCWR), the Integral Primary System Reactor (IPSR), and the Next Generation Candu (CANDU-NG). The concepts cover a wide range of thermal and power outputs and operating temperature (see Table 1). The SCWR has a thermal rating of 900 MW_{th} to 3,800 MW_{th}. The CANDU-NG is designed for the thermal power range of 400 MW_{th} to 1,200 MW_{th}. The IPSR is a smaller system with powers envisioned from 30 MW_{th} to 300 MW_{th}. In general the water-cooled concepts operate in temperature ranges typical of current systems, up to 330°C. The exception is the Super Critical Water Reactor that has variants approaching 625°C. This is below the threshold for the thermochemical processes for hydrogen production, but may be suitable for some other medium temperature process heat applications. However, all electricity generators including water reactors can produce hydrogen through electrolysis methods. Increases in efficiencies and new strategies for optimizing electrolysis techniques such as hot electrolysis may make these systems attractive for hydrogen production. Finally, all water systems operate at elevated pressures. The IPSR operates at 3 to 15 MPa, the CANDU-NG at 13 MPa, and the SCWR at 22 MPa. Intermediate systems will be needed to convert thermal energy to lower pressure fluids used in industrial applications.

All of the water-cooled concepts can be used for bottoming cycles that would include district heating and desalination. However, as noted below, in cases in which the Rankine cycle is used for power conversion, these bottoming cycles result in an efficiency penalty, so the value of the product (fresh water or district heat to displace CO_2 generating heating oil) would have to be evaluated against the lost electricity production.

Table 1. Potential for energy products applications of the most promising Generation IV Water-Cooled Reactor Systems.

Reactor		SCWR	IPSR	CANDU-NG
Thermal Power	MW	900–3800	100–900	1100–3300
Electric Power	MW	200–1700	30–300	400–1200
Outlet temperature	°C	400–625	230–330	330
Primary pressure	MPa	22	3–15	13
Hydrogen production		• Naphtha • CH_4	No	No
Desalination of water		Yes	Yes	Yes
High temperature process heat		• Petroleum refineries • Desulfurization of heavy oil	No	No
District heating		Yes	Yes	Yes

3.2 Evaluation of Gas-Cooled Reactor Concepts for Other Energy Missions

Four gas-cooled reactor concepts sets have been identified. They include the Pebble Bed Reactor (PBR), the Prismatic Reactor (PMR), the Gas-Cooled Fast Reactor (GFR), and the Very High Temperature Reactor (VHTR) (see Table 2). The power levels are 250 MW_{th} for the PBR and 600 MW_{th} for the other reactor types. Helium coolant temperatures at the outlet of the reactor pressure vessel are 850°C for the PBR, PMR and the GFR and 950–1,100°C for the VHTR. Helium coolant pressures of all gas-cooled reactor concept sets are approximately 7.8 MPa. These operating pressures enhance the coolant capacity to transmit heat. The mission of all the concepts sets is to supply high-temperature heat.

The nuclear heat energy of all concepts can be applied to both electricity generation and direct heat use such as hydrogen production, process heat, and other applications. Some of the heat usually discharged to the environment can be used for desalination and district heating as a bottoming cycle. Accordingly, total heat utilization efficiency, defined as (total heat utilized)/(reactor thermal output), can be up to 70–80%, compared to about 33% for existing LWRs.

High temperature is generally required to increase efficiency in thermal conversion cycles. The thermal efficiency for electricity generation can be as high as 44–54% by using a direct Brayton cycle utilizing recuperators. This is competitive with those advanced combined thermal power plants using natural gas.

The other mission of gas-cooled reactor concepts sets is to expand the number of possible uses of thermal energy. The PBR, PMR, and GFR can provide heat for industrial processes and hydrogen production such as for the Ca-Br thermochemical process and for methane-steam reforming with heat input temperatures below 850°C. The VHTR can provide high-temperature heat for most of the heat application processes such as iron reduction, the I-S thermochemical process for hydrogen production, and other needs.

Table 2. Potential for energy products applications of the most promising Generation IV Gas-Cooled Reactor Systems.

Reactor		PBR	PMR	GFR	VHTR
Thermal Power	MW	250	600	600	600
Electric Power	MW	110	286	288	300-360
Outlet temperature	°C	850	850	850	950-1300
Primary pressure	MPa	7.75	7.07	7.0	6.8-8.0
Hydrogen production		• Naphtha • CH_4	yes yes	yes yes	I-S, CH_4, Hot steam electrolysis
Desalination of water		Yes	yes	yes	yes
High temperature process heat		• Petroleum refineries • Desulfurization of heavy oil	yes	yes	yes
District heating		Yes	yes	yes	yes

Nuclear power systems must be located in the vicinity of markets to supply the heat demand of industries. Gas-cooled reactors can meet the requirements and can also safely and stably connect with various chemical plants because of their superior safety.

In contrast to the Rankine cycle used by steam turbines, the Brayton cycle can be efficiently combined with a bottoming cycle such as water desalination and district heating at temperatures of 100°C to 150°C. Thermochemical processes can also be combined because it has at least one exothermic chemical reaction. Thus, cogeneration such as electricity/desalination or district heating and hydrogen/desalination or district heating can increase the total heat utilization efficiency up to 70%–80%. This is very effective in reducing the heat discharged to the environment and reducing overall green house emissions by displacing power production from other CO_2 emitting sources.

3.3 Evaluation of Liquid Metal Cooled Reactor Concepts for Other Energy Missions

All concepts in the liquid metal systems category are driven toward three particular objectives: medium to large-scale electrical power production, resource utilization, and complete fuel cycles. These concepts have been optimized for the power production mission and, for the most part, have not been designed or extensively evaluated for alternative energy product production. This is not to imply the technologies proposed for these concepts cannot be used for alternate mission, but to date, they have been designed and optimized for other objectives.

There are some distinct differences and many common themes behind the liquid metal cooled reactor systems. Most of these concepts operate with core outlet temperatures in the 500–560°C range (see Table 3). That puts all of these concepts at too low a temperature to be able to effectively use their core heat for hydrogen production applications through direct thermochemical methods which currently require a minimum of 600°C for some advanced technological opportunities and may require more than

Table 3. Potential for energy products applications of the most promising Generation IV Liquid Metal Cooled Reactor Systems.

Reactor		L1	L2	L4	L6
Thermal Power	MW	2,000–4,000	400–1,200	~1,000	125–1,000
Electric Power	MW	800–1,500	150–500	2,400	50–350
Outlet temperature	°C	550	530	540	540-780
Primary pressure	MPa	0.1	0.1	0.1	0.1
Hydrogen production		Yes[a]	Yes[a]	Yes[a]	Yes[a]
Desalination of water		Yes	Yes	Yes	Yes
High temperature process heat		No	No	No	Depending on requirements
District heating		Yes	Yes	Yes	Yes

a. The medium temperature liquid metal systems would contribute to hydrogen production in the so-called "symbiotic" approaches through nuclear-assisted steam reforming of natural gas and the membrane reformer. The steam reformer can produce hydrogen at medium temperatures (less than 600°C) by using a membrane for separating hydrogen or an absorber for absorbing carbon dioxide. However, these processes are not economically competitive at the present time and no concrete technical ideas have been advanced for economically producing hydrogen with a steam reformer at medium temperatures.

900°C for efficient hydrogen production. One concept, a lead-cooled reactor with its plutonium-uranium-minor actinide fuel in a nitride matrix, has a core exit temperature of 780°C. This meets the anticipated temperature requirements for the calcium-bromine hydrogen production process, but is outside the 850°C to 1,000°C temperature range needed for the more generally acceptable iodine-sulfur process. However, as noted above, intermediate strategies for hydrogen production could include nuclear-assisted steam reforming of methane. Several of the liquid metal systems, including sodium cooled reactors, could play a role using hybrid approaches to meet temperature requirements. In addition, CO_2 can be reduced through sorption removal or membrane techniques.

Liquid metal systems can also contribute to hydrogen production through electrolysis. Electricity production accompanied by bottoming cycles could make use of the waste heat after electricity is generated. As noted, these applications could include district heating, and desalination of seawater or water from other nonpotable sources.

Almost all of the liquid metal concepts have the characteristic that they are designed to operate at relatively high thermal powers (significantly more than 150 MW_{th}), which may make them less attractive for alternative energy product applications. One concept approaches the lower potentially attractive alternate energy products power range, but has a core exit temperature of about 560°C. As a result, this concept does not fit into the thermochemical hydrogen production domain. It could still be useful for alternative hydrogen production approaches as well as process heat and district heating applications. All of the other liquid metal concepts are designed to operate at much higher power levels since they have been optimized for electrical power production. With significant design effort their technological basis could be used for process heat, but the high temperature capability Pb-cooled concept is most suited for design efforts for application to thermo-chemical hydrogen production.

Since most of these concepts use an intermediate loop to isolate the reactor's core form the electrical power generation system there is a natural additional barrier to tritium migration, thus it is expected that product contamination in these liquid metal reactor concepts could be minimized by their present design understanding. However, if an intermediate loop were not used by any of these concepts, then thorough analysis would be necessary prior to their deployment as an alternate energy product production driver.

Inherent safety is claimed to be one of the dominant driving capabilities for liquid metal concepts. This could nicely facilitate the co-location of these plants close to the complex thermo chemical plants needed for alternate energy product production.

3.4 Evaluation of Non-Classical Reactor Concepts for Other Energy Missions

The three concepts advanced by the Non-Classical Working Group (TWG4) are the Molten Salt Reactor (MSR), the Vapor Core Reactor (VCR), and the Advanced High Temperature Reactor (AHTR) (see Table 4). The mission of the MSR is the transmutation of actinides while producing significant amounts of electricity in order to defray its operating costs. The VCR operates with a UF_4 fuel at sufficiently high temperatures to vaporize the fuel. The AHTR is essentially a prismatic graphite-moderated, coated, particle fueled reactor in which the coolant is not helium but rather molten salt. Both the VCR and the AHTR have primary missions to produce heat at very high temperatures for use either in efficient electrical generation or in the production of hydrogen and high-grade process heat.

Table 4. Potential for energy products applications of the most promising Generation IV Non-Classical Reactor Systems.

Reactor		Molten Salt Reactor	Gas Core Reactor	AHTR
Thermal Power	MW	2,250	1,675	300–2,000
Electric Power	MW	1,000	1,000	150–900
Outlet temperature	°C	704	1,527	1,000
Primary pressure	MPa	0.520	5.00	0.5
Hydrogen production		• Ca-Br • HT electrolytic	All thermo-chemical	• S-I • UT-3
Desalination of water		Yes	Yes	Yes
High temperature process heat		• Petroleum refineries • Desulfurization of heavy oil • Concern for tritium migration	Temperature is certainly high enough. Concern for materials and FP/T migration into secondary	Yes, salt is attractive heat transport medium
District heating		Yes, as a bottoming application	Yes, but a poor use of the heat	Yes, though distribution is an obstacle

The thermal power of the MSR is nominally 2,250 MW_{th}, though the power is not limited by inherent reactor characteristics. Since the molten salt would be drained into geometrically subcritical tank in the event of a reactor scram or overpower, decay heat removal does not pose a limitation on reactor size. Since the nominal outlet temperature is 704°C, the generation efficiency is about 45% and the electrical output is 1,000 MW_e. The pressure of the system is low, with a design pressure of 520 kPa to allow for pumping losses and hydrostatic head. The outlet temperature is limited by heat exchanger and reactor vessel liner materials rather than by fuel temperatures. Development of improvement heat exchanger and vessel materials could lead to outlet temperatures of about 800°C, making the reactor more attractive for thermochemical hydrogen production. Because of the relatively good electrical generation efficiency, the reactor could also be used for high temperature electrolytic production of hydrogen. Conceivably higher temperature variations of the MSR might be feasible to meet the requirements for hydrogen with Ca-Br thermochemical process. The MSR could also be used for desalination and for industrial process heat, such as oil refining. However the presence of tritium in the molten salt due to ternary fission and perhaps due to reactions with lithium and beryllium in the salt poses a safety and product contamination concern, and will require an intermediate loop and heat exchanger development. The MSR is also suitable for district heating, though the more effective use of the reactor’s output would be to supply district heating at the bottom of a Brayton cycle for electrical generation.

The VCR has the highest outlet temperature of any of the concepts. The temperature is limited by reactor vessel materials, if electricity to be generated in an MHD channel and by heat exchanger materials if the heat is to be used for other energy products. The requirements on a heat exchanger are made more severe by the 5.0 MPa pressure of the fuel. The reactor has sufficient temperature for all energy product requirements, but the demands of heat exchanger materials and for barriers against fission product and tritium migration present major challenges.

The AHTR produces heat at a pressure and temperature that are quite amenable to hydrogen production and process heat. The molten salt coolant can be at temperatures of 1,000°C and at pressures of 0.5 MPa. The reactor power is limited by the need for passive heat removal in the event coolant is lost.

4. CROSSCUT ISSUES AMONG GENERATION IV CONCEPTS FOR THE ENERGY PRODUCTS MISSIONS

The nonelectric missions may impose new requirements for Generation IV concepts. In this section, a number of these issues are considered.

By way of introduction, a general observation is in order. The historical role of electricity production that nuclear power has played has a profound influence on the thinking going into Generation IV designs. The Generation IV concepts have often been implicitly conceived for the electricity generation missions. As a result, issues relating to other missions may be overlooked or are not considered because the requirements for nuclear generation for these missions are not yet well known.

In Table 5, the research and development issues are presented and a brief description of the R&D activity. An indication of the relevance of the technology gap is shown, as well as the technical readiness level. The priority of the work is evaluated as critical to resolve a key feasibility or viability issue, essential to reach a minimum targeted level or performance or to resolve key technology or performance uncertainties, or important to enhance performance or resolve choices among viable technical options. The time scales to carry out the work are also provided.

This section summarizes several crosscut issues identified for the energy products missions.

Table 5. R&D for Generation IV Systems for other energy systems.

Technical Gap/Issue					R&D Items				
Subsystem	Gap Label	Brief Description of Gap/Issue	Signifi. of Gap (a)	Current TRL (b)	Activity Label	Brief Description of R&D Activity	Priority (c)	Time (d)	Est. cost range in (Millions)
Temperature	EP1	Temperature capability of various Gen IV concepts Qualifies concept to serve various energy product missions.	P	3	EP1a	An increase of 80˚C or 100˚C in coolant outlet temperature may qualify a concept for an additional energy product mission. The R&D activity would be to assess capabilities of various concepts to go to slightly higher temperatures.	1	M	2.0
Size of Plants	EP2	Because of the size needed for some industrial applications, smaller power levels down to even 50 MWth may be needed.	O	2	EP2a	Assess capability of Gen IV concepts to be designed for lower powers.	1	S	1.5
Product Quality	EP3	Quality of the final product, especially with respect to contamination by tritium, could be a determining factor in the use of Gen IV concepts for alternative missions.	P	2-3	EP3a	Examine sources of tritium to the final product from ternary fission and activation products, and determine ways to reduce tritium in the product.	2	M	2.0
Integrated Safety	EP4	The safety implications of a nuclear power plant coupled to high temperature industrial processes.	P	3	EP4a	Examine safety requirements, methodologies and assessments of chemical processes in conjunction with Gen IV reactor concepts.	2	M	2.0

Table 5. (continued.)

Technical Gap/Issue					R&D Items				
Subsystem	Gap Label	Brief Description of Gap/Issue	Signifi. of Gap (a)	Current TRL (b)	Activity Label	Brief Description of R&D Activity	Priority (c)	Time (d)	Est. cost range in (Millions)
Inherent Safety	EP5	The "perceived" safety of a nuclear power plant located at an existing industrial site such as a refinery, which itself may be may be located in an urban or near-urban setting, will be important.	V	2	EP5a	The safety perceptions of both industry and the public, especially in nearby communities, for the presence of nuclear heat sources must be understood and addressed.	2	VL	2.0
Load Requirements	EP6	Industrial processed may have significantly different loads and load patterns than electricity generation.	O	4	EP6a	R&D is needed to determine capabilities of Gen IV concepts to operate on different duty cycles and reactor cycles to meet industrial user needs.	3	M	1.8
Intermediate Heat Transfer Loops	EP7	Intermediate loops of various sizes and lengths may be needed to deliver heat to the user site.	P	4	EP7a	R&D is needed to determine optimum size, performance, heat losses and other parameters to match Gen IV system output with user needs.	2	M	1.5
Modular Systems	EP8	Use of modular systems to serve industrial users may require distribution of small reactors over an industrial site.	O	4	EP8a	Examination is needed of how much separation can exist between reactors and still share common facilities such as control rooms, spent fuel facilities, etc.	3	M	0.8
Co-Generation	EP9	Co-generation opportunities for Gen IV systems can expand the range of missions and increase overall efficiencies in the use of primary heat.	O	5	EP9a	Development of optimized co-generations systems.	3	S	1.4
Other Industrial Applications	EP10	Gen IV systems can serve a wide variety of non-electricity applications.	P-O	3	EP10a	R&D is needed to match reactor supply characteristics to load needs including temperatures, pressures, flow rates, duty cycles and other requirements.	2	M	30.0

a. Indicate relevance of technology gap: V = concept viability, P = Performance, O = design optimization

b. Indicate technical readiness level (1, 2, 3, 4, or 5); see EMG Final Screening Document

c. Indicate priority of R&D activity:

1 = critical (needed to resolve a key feasibility or viability issue)

2 = essential (needed to reach a minimum targeted level of performance, or to resolve key technology or performance uncertainties)

3 = important (needed to enhance performance or resolve the choice between viable technical options)

d. Indicate time required to perform R&D: S = short (<2y), M = medium (2-5y), L = long (5-10y), VL = very long (>10y)

4.1 Temperature

For the hydrogen mission, for the thermochemical processes, the capability of a reactor to deliver process heat at a certain temperature may be the main discriminator among concepts. Currently the iodine-sulfur process appears to require temperatures in the range of 900°C to 1,000°C. The calcium-bromine process is in the range of 725°C to 800°C. Research is underway on a number of other processes as well such as direct contact pyrolysis and conversion of agricultural feedstock that may further lower the temperature ranges. However, for the purposes of this evaluation, about 700°C was taken to be minimum temperature for potential hydrogen/process heat applications. At lower temperatures, it is foreseen that other energy product uses of nuclear heat would be from bottoming cycles after electricity is generated. As discussed above, these applications could include district heating and desalination of seawater or water from other nonpotable sources. With regard to district heating, it is noted that a nuclear supplied district heating network has operated for almost two decades in Switzerland. In addition, some major metropolitan areas such as Moscow, and many other cities in Russia, the Former Soviet Union, and Eastern Europe are already well equipped with the infrastructure to distribute district heating from a central power plant. If or when there is a motivation to replace the CO_2 emitting plants with a non-emitting source, a nuclear power plant designed for these applications could be a viable, and perhaps the only, candidate.

4.2 Size of Plants

Sizing requirements for nontraditional applications may stretch conceived designs to be both larger and smaller than are currently the norm. The use of hydrogen in petroleum refining is a near term opportunity. The most recently ordered hydrogen plants produce 200–300 million cubic feet a day from steam reforming of natural gas. Three hundred million cubic feet per day of hydrogen, if burnt, would produce ~1,000 Mw. Using the IS cycle, 2,000 MW_{th} of high-temperature heat is required to produce hydrogen at this rate. The smallest Generation IV concepts are aimed at the order of 100 MW_e and greater, although the Pb/Pb-Bi concepts may be adaptable to the lower power range. Further evaluation is needed for the adaptability of current Generation IV designs for smaller applications.

Alternatively, for central station hydrogen generation, quite large plants could ultimately be needed as well. Hydrogen plants currently under design using non-nuclear sources would require a reactor (assuming 50% production efficiency) of 1,600 MW_{th}. This is well within current parameters, but depending how the hydrogen market evolves over the next few decades, reactors conceivably twice or three times this output may be needed to meet market requirements. An evaluation of scale up of the thermal power of Generation IV designs would be helpful.

4.3 Product Quality

Occasionally in public meetings and the nontechnical publications, questions are raised about dangers of nuclear electricity because the electrons generated in the process might be radioactive. While this concern can be readily demonstrated to be without substance, it must be kept in mind that three of the potential Generation IV energy products—hydrogen, fresh water, and district heat will go directly to consumers. The question of “product quality” or “product contamination” may become critical, with the most probable concern focusing on tritium. It should be noted that this has been successfully addressed as a major issue in the Refuna district heating project in Switzerland. However, if there is the potential for hydrogen and drinking/agricultural water to have levels of tritium that the public perceives as a risk, the opportunities for market penetration by nuclear could be impeded.

Two sources of tritium must be considered. Tritium can be produced both as a ternary fission product and as an activation product. The diffusion of tritium through heat exchangers and other components is difficult to limit. It is likely that those Generation IV concepts that can meet the temperature requirements and demonstrate reduced amounts of tritium going into energy products may have an advantage. The best approach is not to generate tritium. This is determined by choice of materials. Secondly, R&D is needed to limit tritium diffusion. This can be achieved by introducing effective barriers to diffusion. Finally, tritium can be separated from hydrogen through the use of purification systems. However, this becomes an added cost in producing the product. Evaluation of Generation IV concepts to determine tritium generation, diffusion, and transport characteristics is needed.

4.4 Integrated Safety

The HTTR plant in Japan produces hydrogen through methane steam reforming. The plant that uses the high temperature heat from the reactor is located approximately 80 meters away. This was designed to achieve separation, which was also required by the site layout because the reforming plant had to be on the other side of a road. However, a loss of 20°C in the heat duct is lost over the 80 meters. This is not a huge loss, but does diminish the efficiency of the process. R&D on heat transport technology between the reactor and the chemical process plant will be required to address the question of the integrated safety of a nuclear source with a hydrogen production plant. The requirements for this type of plant will have to be specifically defined. For current industrial hydrogen production sites associated with refineries, the hydrogen facility is generally not considered the most significant risk driver. In addition, in the past, fast reactor designs were able to sufficiently isolate the reactor core from possible sodium-steam interaction in the case of tube failures in the steam generator. So this is a good background to suggest that a nuclear heat source can be coupled with a chemical plant and meet safety requirements. However, the specifics of these requirements will have to be developed. Close interaction with the chemical and refining industries will be needed to do this, especially since they would be the customers of these integrated systems. An R&D approach will be to examine how risk is evaluated in the chemical industry. These approaches must be integrated and reconciled with risk and safety requirements used in evaluating nuclear installations. For example, in the HTTR plant, large, high-temperature isolation valves are being developed and will be placed in the helium line leading to the reforming plant. Other new requirements may emerge about reliability of heat exchangers as well to meet these integrated plant safety needs. In the context of chemical plants, it will be necessary to understand on energetic accidents on a deterministic basis. Events beyond the design basis accidents must be assessed for the reactor using PRA methods.

4.5 Inherent Safety

All Generation IV concepts incorporate enhanced safety. These improvements have been emanated from a “nuclear” viewpoint. However, inherent safety may become an “enabling” feature for the use of nuclear systems for new energy product applications. The sites may be in existing industrial plant located in the vicinity of urban centers. It is not yet possible to define what these additional safety characteristics are, but innovative thinking would be fruitful on what safety means to a potential industrial customer, how these features can be incorporated and how they would be perceived. There may be other aspects of Generation IV plants that are not yet fully utilized for this purpose. Other design and inherent features might be developed. It is suggested that Generation IV concepts be considered from the perspective of “enhanced” safety, as it would be seen by potential customers.

4.6 Coupled Plant Dynamics

The needs of other energy product processes could be different than the requirements for electricity generation. These differences could include the frequency and length of refueling outages, duty cycles, and performance during startups and transients of the chemical plants, and capability of the reactor to incorporate excess reactivity to compensate for xenon oscillations. As noted earlier, reactors that serve industrial needs may be of different power levels as electricity generators, but these facilities may not be part of a network or grid. These requirements may also be determined by the ability to store or distribute the product. The flexibility of Generation IV concepts may be important to satisfy other energy product markets.

4.7 Intermediate Heat Transfer Loops

Studies of potential nonelectrical applications call the attention to the fact that many industrial sites already use high temperature (900°C) salts at ambient or near-ambient pressure as a heat transport medium. While this approach may be regarded as exotic from the nuclear perspective, in the chemical and smelting industries liquid metals and hot, high-pressure helium are not generally used for heat transport. If nuclear reactors are to supply process heat at 900°C to new uses, it may be necessary to couple Generation IV systems to heat transfer systems of existing technologies. In addition, because of the size of chemical and industrial facilities and because of the need to centrally or remotely locate the nuclear reactor(s), the intermediate loop may be required to transport tens of megawatts of thermal energy at 600–900°C for distances of a few kilometers.

At lower temperatures, many industrial processes require steam at 150–250°C for drying, melting, distilling, cooking and endothermic chemical reactions. In order to achieve good overall thermal utilization, heat may be supplied to a high temperature process at 600–900°C and steam at 150–250°C may be generated from the molten salt thereafter. Alternatively, the reactor coolant may be used for both salt heating and steam generation.

Research will be necessary to development the heat transport medium and components to serve these needs for process heat. Existing experience and technologies can aid in the selection of molten salts. The salts will be chosen on the basis of heat capacity, viscosity, operating temperature, safety and toxicity in handling and the consequences of a spill of the hot salt onto the ground or plant floor.

R&D will also be needed on high temperature heat exchangers involving gas-to-salt, liquid metal-to-salt, or supercritical steam-to-salt. Special considerations for heat exchangers because of their use in conjunction with nuclear systems include tritium and fission product barriers, preventing the pressurization of either system in the event of a heat exchanger failure and the ability to replace the components with minimum worker radiological exposure. Other components of heat transport system, such as pumps, valves, piping, and insulation need not be of nuclear grade and can be of existing industry standards. Regarding heat exchangers, in addition to the applications mentioned above, quite different needs may arise and it may become necessary to transfer the nuclear heat via an intermediate heat exchanger (IHX) to nitrogen or carbon dioxide. These would represent components not found in current nuclear systems, and research and development would be required for these applications. Finally, industrial needs for high temperature/high quality steam may also be a market for Generation IV systems.

4.8 Modular Systems

For industrial applications, new definitions of modularity may arise. For electricity generation, a generating station will be composed of several adjacent modules. This allows for shared facilities such as a common control room, spent fuel pools, and other services. An estimate has been made that $150 million of common requirements should be associated with the first module. However, at a very large industrial site such as a major refinery, modules may be located some distance apart, perhaps a few hundred meters to a kilometer or more so they would be near the energy demand center, and to avoid losses in transporting high energy heat around the site. Does this arrangement still qualify as being modular, and can the common systems (control rooms and other facilities) still be located at one location and take advantage of shared costs? In addition to the use of common facilities, more economical energy production can be achieved with modularity and standardization coupled through factory fabrication.

4.9 Role of the Brayton Cycle and Co-Generation

Thermodynamic analysis indicates the advantage of the Brayton cycle when coupled with other lower temperature processes. An examination of the temperature-entropy diagram shows that heat can be removed without the same penalties in efficiency than would occur for the Rankine cycle. Usually the Brayton cycle is only considered in conjunction with gas-cooled reactors. However, the Brayton cycle is appropriate with other high temperature concepts and may be the best approach when optimizing plants with multiple functions. Numerous studies have been carried out examining co-generation. This is worthwhile literature to review in conjunction with Generation IV concepts. In addition, advances such as the use of supercritical CO_2 Brayton cycles may increase efficiencies for Generation IV systems while maintaining the attractiveness of the Brayton cycle with nuclear.

Every nuclear power station can provide heat for desalination or district heating because the required temperature range for these applications is no higher than 200˚C. However, it should be noted that the combination of heat utilization processes such as electricity generation by the Rankine cycle and desalination, termed co-generation, has limited attraction because of the desire to maximize efficiency.

In facilities for electricity generation, coolant temperatures at the heat exchanger for the discharge of heat to the low temperature heat sink is maintained as close atmospheric temperature as possible in order to reach the highest achievable thermal efficiency. The maximum efficiency for a heat cycle is defined by the Carnot cycle as $1–T_L/T_H$. In the Rankine cycle, the temperature at the heat exchanger (condenser) is nearly equal to atmospheric temperature, and there is no temperature difference between the inlet and outlet of the heat exchanger because heat is discharged to the low temperature heat sink by means of condensation of steam. If 150°C is needed at the heat exchanger of Rankine cycle for desalination or district heating, the thermal efficiency is diminished by increased temperature at the condenser.

On the other hand, in the Brayton Cycle, coolant temperatures range from 150°C down to 30°C at the heat exchanger to discharge heat to the low temperature heat sink. Therefore the heat in the range of 150°C down to 30°C can be used for purposes such as desalination or district heating. Also, in thermochemical processes like the I-S process, the heat at around 100–150°C can be used because all thermochemical processes have at least one heat generation exothermic chemical reaction.

It is concluded that the Brayton cycle or thermochemical processes for hydrogen production can be combined with desalination or district heating as a co-generation system without reducing the thermal efficiency of electricity or hydrogen generation. However, for co-generation of Rankine cycle and desalination or district heating, thermal efficiency of the cycle for electricity generation is decreased.

4.10 Other Industrial Applications

As shown in Figure 2, a number of industrial processes can use medium temperature and high temperature nuclear heat. These can include steel manufacture, pulp and paper production, and a variety of chemical products needing high temperature steam. Current studies suggest that the aluminum industry may be a near term opportunity for nuclear process heat. In the U.S., this industry is largely located in the Northwest, some in relatively remote locations near hydroelectric sites, to take advantage of low cost electricity from the Bonneville Power Authority. However, with the low snow years and the pressure for higher priced electricity in the California market, shifts have occurred. Some plants have found it economically attractive to resell their electricity at much higher prices on the spot market than to produce aluminum. Reliability of energy sources is important in aluminum production since once crucibles cool down, they can no longer be restarted. If Generation IV concepts can be shown to deliver process heat reliably over extended periods, aluminum smelters may be potential markets.

Other similar applications could be to aid oil recovery in shale formations or tar sands. The tar sands of Northern Alberta might be a good example. Because of the nature or the formation, heat is needed to decrease viscosity in order to recover the oil. In addition, it is required to produce a low hydrogen-to-carbon product, so generation of hydrogen could be used to increase the hydrogen-to-carbon ratio that would add value the product at the site of manufacture.

4.11 Research and Development Relating to Other Energy Product Missions

In addition to the ten areas for crosscut R&D discussed above, other R&D needs are identified specifically for the other energy missions, as well for advanced energy conversion. These are discussed in the two sections below and shown in Table 6.

4.11.1 R&D on Generation IV Systems for Other Energy Missions

Several R&D areas have been identified relating to thermochemical hydrogen production processes such as iodine-sulfur and calcium-bromine. Associated areas identified include materials compatibility, corrosion, lifetime and selection, thermochemical properties measurements and databases, rate constant measurements for the chemical processes, thermodynamic optimization and flowsheets, benchscale integral tests, pilot plants, and demonstration plants. These sets of R&D needs will be different for the two different processes.

In addition, as listed in the accompanying tables, continued activities are needed for optimized desalination processes to be linked to nuclear generation.

4.11.2 R&D for Advanced Energy Conversion

Electricity will continue to be a product from nuclear energy generation. Work is needed on advanced conversion processes including supercritical CO_2 Brayton cycles, and supercritical steam Rankine cycles. Specific activities are listed in Table 6.

Table 6. R&D on energy products and advanced energy conversion.

Technical gap/issue					R&D items				
Subsystem	Gap Label	Brief Description of Gap/Issue	Signific. of Gap (a)	Current TRL (b)	Activity Label	Brief Description of R&D Activity	Priority (c)	Time (d)	Est. Cost Range (Millions)
Energy Processes and Products	EP11A	Thermochemical water cracking (iodine-sulfur and calcium-bromine)	V	2	EP11Aa	Materials selection	2	M	20
					EP11Ab	Thermochemical properties measurements & database	2	M	15
					EP11Ac	Rate constant measurements	2	M	10
					EP11Ad	Thermodynamic optimization and flow sheet	2	M	5

Table 6. (continued.)

Technical gap/issue					R&D items				
Subsystem	Gap Label	Brief Description of Gap/Issue	Signific. of Gap (a)	Current TRL (b)	Activity Label	Brief Description of R&D Activity	Priority (c)	Time (d)	Est. Cost Range (Millions)
					EP11Ae	Bench scale integral test	2	M	10
					EP11Af	Small scale prototype test	2	M	33
					EP11Ag	Ca support selection (specific for Ca-Br process)	2	M	7
	EP11B	Desalination	P	4	EP11Ba	Develop models/adapt IAEA model for nuclear desalination	2	S	5
					EP11Bb	Monitor R&D progress by others on reverse osmosis and multi-effects distillation	2	S	1.5
					EP11Bc	Monitor developments by others of multistage flash heat exchangers, crud control and brine disposition	2	S	1.5
					EP11Bd	Evaluate commercial opportunities for coupling to product extraction from brine: - uranium - other	2	S	2.0
Energy Converters	EP12A	Supercritical CO_2 Brayton cycles	P	2	EP12Aa	Thermodynamic optimization	2	M	3.0
					EP12Ab	Materials selections - heat exchangers - recuperator - turbine and blades	2	M	3.0
					EP12Ac	Small scale testing - turbine - recuperator	2	L	9.5
	EP12B	Supercritical Steam Rankine cycle	P	4	EP12Ba	Review fossil plant experience	2	S	5
					EP12Bb	Monitor work by others on SC steam Rankine cycle - TWG-1 - Russian BREST Program	2	S	7
					EP12Bc	Economic comparisons	3	S	3

a. Indicate relevance of technology gap: V = concept viability, P = performance, O = design optimization.

b. Indicate technical readiness level (1, 2, 3, 4, or 5); see EMG Final Screening Document.

c. Indicate priority of R&D activity:

1 = critical (needed to resolve a key feasibility or viability issue)

2 = essential (needed to reach a minimum targeted level of performance, or to resolve key technology or performance uncertainties)

3 = important (needed to enhance performance or resolve the choice between viable technical options).

d. Indicate time required to perform R&D: S = short (<2y), M = medium (2-5y), L = long (5-10y), VL = very long (>10y).

5. ENERGY PRODUCT MARKETS—OPPORTUNITIES AND CONCLUSIONS

As the energy picture develops and Generation IV concepts reach commercial viability, the competitors to nuclear power will be shifting their positions too. It is important to focus on what the markets and customers want, and what is needed to make nuclear attractive under the circumstances that will occur over the next few decades. Much thought has gone into this question regarding nuclear generated electricity. Similar considerations will be required as nuclear plants are used for other purposes. It is suggested that as opposed to waiting for the “day to come” for nuclear power, the nuclear community should try in an active way to make nuclear a better competitor for new energy products whether it is in terms of cost or other attributes. Further, it is imperative to recognize that the requirements, conditions and thresholds may be different in each country.

In conclusion, the opportunities for other energy products from nuclear systems appear to be immense. Generation IV concepts meet a wide range of temperature requirements which allow nuclear to be considered for a variety of other energy missions. Nuclear already provides, by far, the largest fraction of non-CO_2 emitting primary energy, and the importance of this attribute is only expected to grow over the years and decades to come. The role of nuclear power in serving the vast energy in a clean, effective, safe manner will ultimately be regarded as the hallmark of this technology.

Appendix A

Generation IV Energy Products Evaluation Methodologies

Appendix A

Generation IV Energy Products Evaluation Methodologies

OVERVIEW

The following discussion is concerned with methods for evaluating the value of energy products that may be obtained from a nuclear power reactor/fuel cycle. Such products include electricity, hydrogen and water, and process heat. The purpose of this discussion is not to address the potential markets for such products, as they are unknowable, but rather to discuss how different nuclear reactor/fuel cycle concepts can be compared in terms of their ability to create them. The goal is to be able to evaluate such relative performance quantitatively.

The ideas presented apply to electricity as well as to other products. However, economic evaluation of electricity production is sufficiently advanced that it will remain an independent evaluation, performed in parallel with that discussed below.

MAXIMUM AVAILABLE WORK ANALYSIS

Fundamentally a nuclear reactor/fuel cycle produces heat at the temperature of the coolant leaving the reactor control volume. What that energy is used for depends on the temperature of the coolant and the design of the devices used to convert it into an alternative energy form such as electricity, or to make a tangible product such as hydrogen or water. The role of the reactor, however, is only to produce the heated coolant. The downstream system used to employ that heated coolant, such as a Rankine cycle power conversion system, exists independent of the reactor itself, although the choice of which system to use may be influenced by the design of the reactor, as with the BWR coupled with a Rankine cycle power conversion system. The point however, is that the merits of the reactor/fuel cycle should be judged from the perspective of being able to produce coolant at a particular temperature. A measure of the highest economic value of such heat is the work that could be extracted from it. Such a measure is the available work (A) defined as:

$$A = Q\,[(T/T_O)-1]$$

where

A	=	the amount of work that can be obtained using a perfect heat engine from the heat
Q	=	amount of heat from the source
T	=	temperature of the reactor outlet coolant
T_O	=	temperature of the ambient environment.

In comparing reactor/fuel cycle concepts in terms of their ability to produce alternative products, a comparison should be made in terms of the ability of the processes to produce available work. This comparison may be made in terms of the usual measures such as costs, time, and other resource demands.

Some products such as process heat used to drive a chemical reaction do not require a conversion of heat into work in order for their creation; however, the maximum available work cost remains the proper measure of the value of the energy used as an input for such processes, as it could alternatively be used for work production. Thus, the opportunity cost of the use of heat for applications other than the production of work must be valued at the highest value of the use of the heat, which is that of the work which could otherwise have been produced.

Similarly, in evaluating the cost of using nuclear heat to drive a particular process, that heat should properly be valued at its availability-based cost, as this cost reflects the price that heat could command in a market.

OTHER CONSTRAINTS

In using a reactor/fuel cycle for creation of a particular product, some product-specific constraints may also be important. An analysis of the value of a particular reactor/fuel cycle for creating a particular product must reflect these constraints (e.g., it would be misleading to evaluate a large power capacity reactor for purposes of providing process heat when the feasible users of such heat can only consume the amounts of heat provided by much smaller capacity reactors). Some of the more important constraints on feasible reactor/fuel cycles of some potential products are summarized in Table A-1.

Table A-1. Important constraints of potentially important reactor/fuel cycle products.

Product	Constraint
Hydrogen	Storage or transportation system processing capacity
Process	Heat user consumption capacity
Heat	Heat user degree of ability to cope with the reactor being shutdown
Desalinated	Water user consumption capacity
Water	Water user ability to cope with the reactor being shutdown

SUMMARY

The general method for comparing the merits of alternative reactor/fuel cycle concepts in terms of their ability to create different energy-based products is in terms of the resource requirements to produce a unit of maximum available work. Such a comparative analysis should also reflect the influences of any important constraints that would restrict the practical realization of the reactor/fuel cycle concept.

Appendix B

Balance of Plant, Energy Products, and Process Heat Applications

Appendix B

Balance of Plant, Energy Products, and Process Heat Applications

INTRODUCTION

A number of Generation IV concepts have the potential to be coupled to several power conversion cycles for electricity production. In addition, cogeneration of electricity and heat and could be used to provide high temperature process heat for a variety of nonelectric applications. One of the most exciting of these process heat applications is the production of hydrogen by thermochemical water splitting. Hydrogen can be a significant market for nuclear energy. In the long term, the market for hydrogen is potentially more than twice the market for electricity. Further, there is already an immediate market for hydrogen in the U.S. chemical process industries that nuclear energy could help fill. Nuclear energy can provide a long-term, stable secure source of hydrogen at reasonable cost. Nuclear production of hydrogen can well become the "enabling technology" for the hydrogen economy.

HYDROGEN PRODUCTION PROCESSES

There are three principal methods for nuclear hydrogen generation using a high temperature reactor (see Figure B-1):

- Water electrolysis and high efficient electricity generation
- Steam reforming of methane and light hydrocarbons
- Thermochemical cycles.

Currently steam reforming of natural gas is the dominating industrial hydrogen production method. It can be coupled to an HTR to substitute the process heat for this endothermic process, thereby gaining much higher yields. To evaluate the different hydrogen production methods, the basic thermal hydraulic relationships are used that govern the efficiency of thermochemical processes for hydrogen production as well as that of electricity generation in combination with electrolysis.

As illustrated in Figure B-2 (left figure), the decomposition of water at low temperatures needs electricity, and hydrogen can be produced with heat only at temperatures higher than T_d because of the minus delta G. Thus, the electricity needs are considerably reduced if the electrolysis is performed at higher temperature levels. As shown in Figure B-2 (right figure), the thermochemical process can produce hydrogen at T_h lower than T_d with only heat by at least two chemical reactions.

Let's consider two different cases for producing hydrogen from water to evaluate thermal efficiency: (1) the case of electricity generation and electrolysis of water, and (2) the case of thermochemical water splitting. Both cases are finally governed by the same formula dependent only on the upper (T_h) and lower (T_c) operational temperature as well as from the dissociation temperature (T_d), which is 4,309 K for auto-thermal water splitting.

$$\eta = [(T_h - T_c) / T_h] * [T_d / (T_d - T_c)]$$

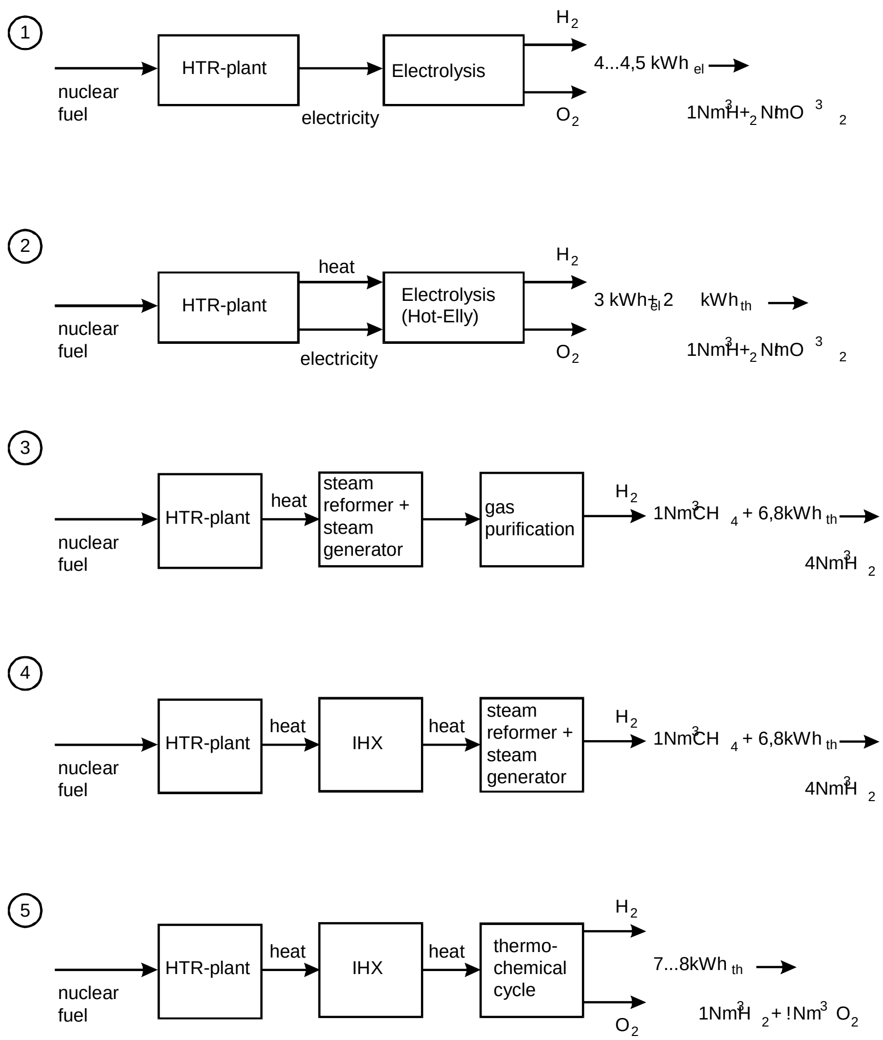

Figure B-1. Various processes to produce hydrogen.

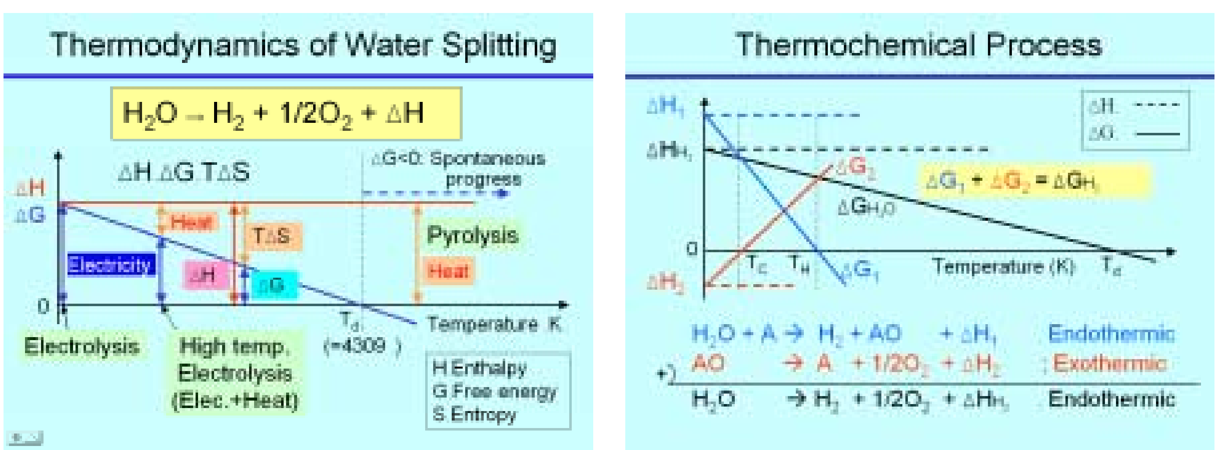

Figure B-2. Analysis of hydrogen production by Electrolysis and Thermochemical Processes.

The following theoretical formula for thermal efficiency has a direct impact on the choice of technical options:

- Operational temperatures of the process and the heat source should be as high as technically feasible

- Thermochemical processes or electricity generation at lower temperatures will always be inferior with regard to the thermal efficiency η,

- Since the dissociation temperature is extremely high, water splitting always needs several successive processes to provide the dissociation energy—electricity generation plus electrolysis (heat), or a follow-up of different endothermic and exothermic chemical processes at lower temperatures.

As a result, the final conversion efficiency is fundamentally independent on any route of conversion technology based on the assumption of the same conditions for input and output.

Enhancing the efficiency for electricity generation and for electrolysis by temperature increase is one option for improving hydrogen production. Electrolysis can be done remotely and decentralized or with direct coupling to the reactor by using the high temperature steam, the so-called “hot electrolysis” route, shown in Figure B-3. This process can benefit extensively, for example, from fuel cell development, which is the inverse process using the same functional elements.

The Very High Temperature Reactor (VHTR) and the Advanced High Temperature Reactor (AHTR) are uniquely well suited for coupling to the iodine-sulfur (I-S) thermochemical water-splitting cycle for hydrogen production. The high temperature heat should make possible the production of hydrogen at high efficiency (~50%) and reasonable cost (~\$1.30/kg H_2). The reactor will be coupled to the chemical process through an intermediate heat exchange loop. The primary reactor coolant will pass through an intermediate heat exchanger and transfer heat to the intermediate loop coolant stream. This stream will transport the heat to the chemical plant where it will be transferred through heat exchangers into the process working fluids. For best performance, the sulfur iodine cycle needs to operate at a peak temperature of about 830°C. To deliver heat to the process at this temperature, the reactor outlet temperature needs to be approximately 100°C higher than the process heat temperature.

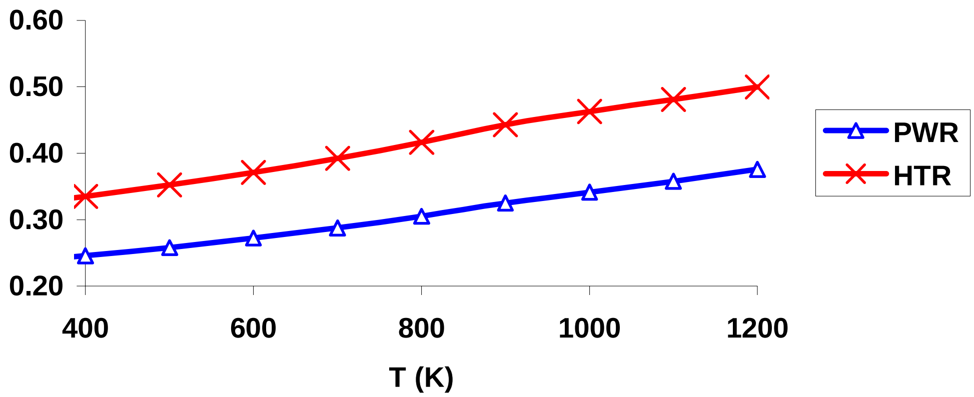

Figure B-3. Efficiency of hot electrolysis using electricity from HTRs or LWRs.

Additional development needs are identified in (1) Modular High Temperature Reactor (MHR) incremental development, (2) the intermediate heat transport loop, and (3) water-splitting processes. In each of these areas, it is possible to build on significant past efforts. The following sections describe the development base and additional development needs for these three areas.

Modular High Temperature Reactor Incremental Development

The need for an approximately 100°C higher reactor outlet temperature and the low pressure of the thermochemical processes will necessitate some design changes, especially for the block core design, due to the higher fuel temperatures in the fuel compacts. The basic approach will be to raise the core outlet temperature without exceeding peak fuel temperature limits (1,230°C). A few design changes should make this possible without raising the critical temperature limits on the fuel or the reactor structural materials. These design changes may include use of a different core inlet temperature, use of smaller diameter fuel rods, more thermal insulation in the cross duct, or other changes that would not change the basic reactor technology, and may not require any substantive R&D efforts.

A design activity to perform a serious conceptual design for the VHTR for hydrogen production (H_2-VHTR) is proposed as part of the DOE NERI activity. This design effort will evaluate and select the design changes from the base GT-MHR that will be needed for the H_2-VHTR. This includes the core mechanical and thermal design, the pressure vessel and cross duct design, the circulator design, and a safety evaluation of the finished H_2-VHTR. This design work will allow reevaluation of the current assessment, which concludes that relatively little specific R&D beyond the circulator development will be needed for the MHR portion of the H_2-VHTR.

Further work will be needed in the area of the circulator. The helium circulator for the primary loop of the H_2-MHR design will be located in the IHX cavity. It will be virtually identical to the circulator designed for the steam cycle MHTGR. It will also parallel the development effort for the circulator in the generic portion of the MHR program, which includes impeller aerodynamic and acoustic tests and prototype tests of the circulator unit in a high-pressure helium test facility (HPTF) under reactor conditions to verify the design. Most of these adaptations can also be used for the PBMR-based designs.

Intermediate Heat Transport Loop

For the case of the iodine-sulfur process, the high temperature heat from the VHTR will be coupled to the iodine-sulfur thermochemical water-splitting cycle by means of an intermediate heat transport loop. In this concept, the working fluid will be pressurized helium or air at a pressure intermediate between the 70 atm of the MHR and the 8–20 atm pressures of the I-S process. In former nuclear process heat projects, the primary reactor pressure was reduced to about 40 atm to limit the differential pressures. Reactor primary loop helium will enter the IHX, located in a well adjacent to the reactor, at 950°C and returned to the reactor at about 500°C. The intermediate loop will operate at an upper temperature of about 900°C and a lower temperature of about 350°C. Lower helium return temperatures could ease the design and material choice for the pressure vessel. The intermediate loop piping will come out of the IHX well and exit the reactor building to transport the heat to the hydrogen process plant. Heat will be transferred into the water-splitting process via heat exchangers that are part of the hydrogen production process. The intermediate loop circulator will be located out of the IHX well and will be very similar to that used in the primary helium loop. The development effort described in the above section for the primary loop helium circulator will also provide information needed for the intermediate loop circulator.

The IHX between the primary and intermediate helium loops will be based on conventional designs. In the former German Prototype Nuclear Process Heat Project (PNP), helix and U-tube IHX have been developed and tested in a 10 MW-scale. The IHX of the HTTR has the same power size. Currently, the printed circuit heat exchanger configuration, similar to those manufactured in the United Kingdom, is favored because of compact size and high efficiency. These heat exchangers are not yet commercially available at the temperature range needed for the H_2-VHTR. Additional design work will be needed, and it is possible that an ASME code will have to be developed for the needed hydrogen production materials. It is anticipated that conventional high temperature metal alloys will meet requirements or alternatively code qualified nickel-chrome Alloy 617 for non-nuclear use up to 980°C.

Other important components are the isolation valves in the hot and cold gas ducts of the intermediate circuit. Their objectives are to separate the reactor system with nuclear standards from a process heat system with non-nuclear standards. Test on coating material of the valve seat focused on anti-seizure and adhesion performance for use in the HTTR. Integrity tests of the valves in full-scale will be necessary. Results from former German tests of two different types of valves and of diverse hot gas ducts should be retrieved. The integrity test against repetitive operation of high-temperature isolation valve has to show the reliable performance after multiple activations. Material development for valves is challenging, but if no material is found for the sheet, other approaches, such as changing the valve for a certain period, could be considered.

Thermochemical Water-Splitting Processes

The concept of producing hydrogen by using a set of chemical reactions to separate water into hydrogen and oxygen at moderate temperatures was developed in 1964. Some 115 different thermochemical water-splitting processes have been identified. Two appear to be well suited for Generation IV systems. These are the iodine-sulfur cycle (I-S) and the calcium-bromine process. This discussion will focus on the iodine-sulfur approach.

Iodine and sulfur-dioxide are added to water as shown in Equation (1) in an exothermic reaction that creates sulfuric acid and hydrogen iodide. These are immiscible and readily separated. The sulfuric acid can be decomposed at about 850°C, releasing the oxygen and recycling the sulfur dioxide (2). The hydrogen iodide can be decomposed at about 450°C, releasing the hydrogen and recycling the iodine. The net effect is the splitting of water into hydrogen and oxygen.

$$2H_2O + SO_2 + I_2 \rightarrow 2HI + H_2SO_4 \qquad 100°C \qquad (1)$$

$$H_2SO_4 \rightarrow SO_2 + H_2O + I_2O_2 \qquad 850°C \qquad (2)$$

$$2HI \rightarrow I_2 + H_2 \qquad 450°C \qquad (3)$$

$$H_2O \rightarrow H_2 + I_2O_2 \qquad (4)$$

The whole process takes in only water and high temperature heat and releases only hydrogen, oxygen, and low temperature heat. All reagents are recycled and there are no effluents. Each of the major chemical reactions of this process was demonstrated. The S-I cycle is projected to have an overall efficiency of about 50%. It is estimated that the plant will achieve about 50% efficiency and may be able to produce hydrogen for as little as $1.30/kg of H_2.

Additional steps in the development of the nuclear-coupled thermochemical hydrogen production processes are to design, build, and operate a laboratory scale, completely integrated, closed loop experiment driven by a non-nuclear heat source. This would take in water and simulated nuclear heat and release hydrogen and oxygen at about 1–10 L/hr. It will provide a convincing proof-of-principle that the nuclear-matched cycles are viable, and will allow verification that the chemical reactions indeed mesh together into a closed cycle. Such experiments would provide confirmation that reagent crossover, impurity build-up, and hydrogen impurity levels are well understood and controlled. Some additional chemical data is needed to design the most efficient cycles. Thermodynamic equilibrium and rate data are needed for the three-phase equilibrium before a large-scale hydrogen plant should be built.

Following this work, a pilot plant will need to be constructed, using fully prototypical materials and technologies. The pilot plant would also operate on non-nuclear heat, simulating heat transfer from a nuclear reactor. The pilot plant would demonstrate the technologies and materials of a full sized plant. It would verify plant control systems and operability and confirm materials performance.

These R&D activities can draw upon and integrate work underway in the U.S., Japan, Germany, and possibly other countries. As note above, specific R&D items include on the IS process include laboratory scale study of hydrogen production, related chemical data, bench-scale and pilot-scale experiments, and demonstration tests with nuclear heat. Additional work would involve studies on assuring product quality, investigation of membrane and substrate technologies, and selection of materials for constructing large-scale plants, to include corrosion tests of commercially available materials, effects on mechanical properties, and determination of any needed surface modifications.

Process Heat Applications

Figure B-4 illustrates a generic design using process heat from a high temperature gas reactor. Several system design and R&D issues are identified. Among these is the IHX. When the heat is used for hydrogen production or other industrial processes, nuclear heat from the core reactor should be transferred into the secondary helium through an IHX to assure system safety. The IHX needs to be of high reliability to provide a boundary between the primary and the secondary helium coolants as well as high thermal efficiency and compactness. Due to these requirements, a plate-fin type compact heat exchanger should be developed to augment heat transfer. There are needs to develop a compact steam reformer, heat exchanger, and other components. Also needed will be a thermal load absorber using high temperature latent heat storage technology. This might be accomplished through an increase of effective thermal conductivity of phase change materials (PCM) by absorbing PCM into porous materials. An estimation of reduction characteristics of thermal loads with PCM would be needed, along with material tests, to evaluate corrosion resistance of metals to PCM.

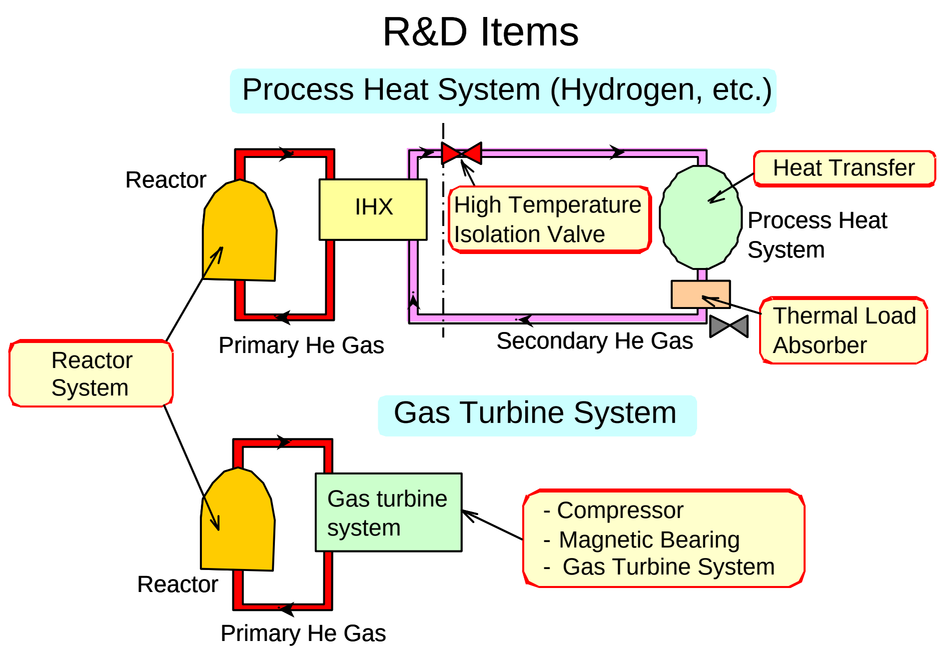

Figure B-4. Generic industrial process using high temperature nuclear heat.

Steam Reforming of Methane Using Nuclear Heat

Steam reforming of methane might represent an early opportunity for the use of nuclear heat in the production of hydrogen. The endothermic steam reforming reaction of methane takes place in a wide temperature range from 500–800°C and above in the presence of a nickel catalyst:

$CH_4 + H_2O \rightarrow CO + 3H_2$ - 206 KJ/mol

$CH_4 + 2\ H_2O \rightarrow CO_2 + 4H_2$ - 165 KJ/mol

High temperatures, low pressures, and low H_2O/CH_4 ratios are suited to achieve low residual CH_4 contents in the reformer gas. CO, which is still contained in the reformer gas, is converted by the exothermal shift reaction:

$CO + H_2O \rightarrow CO_2 + H_2$, + 41 KJ/mol

Figure B-5 shows a flowsheet in which all the heat for the reforming process, steam production, gas purification, and gas compression can be obtained from an HTR.

The steam reformer uses the temperature of the helium (40 bar) between 950 and 700°C and the steam generator heat between 700 and 250°C. The feed gas (H2O/ CH4 ≈ 3/1, p ≈ 40 bar) is preheated to about 500°C and reformed with as maximal process temperature of 800°C. Approximately 85% of the methane is then converted in this first step. The use of reformer gas heat for preheating the feed gas, shift conversion, and methane production are the following steps behind the reformer to get the hydrogen product. A steam turbine plant using co-generation supplies the needed steam and electrical energy for the whole process. CH4 as raw material is converted completely to hydrogen. The total efficiency including the nuclear heat is around 65%. The steam reformer and the steam generator can also be arranged in the IHX circuit. This approach is being used in the HTTR project in Japan.

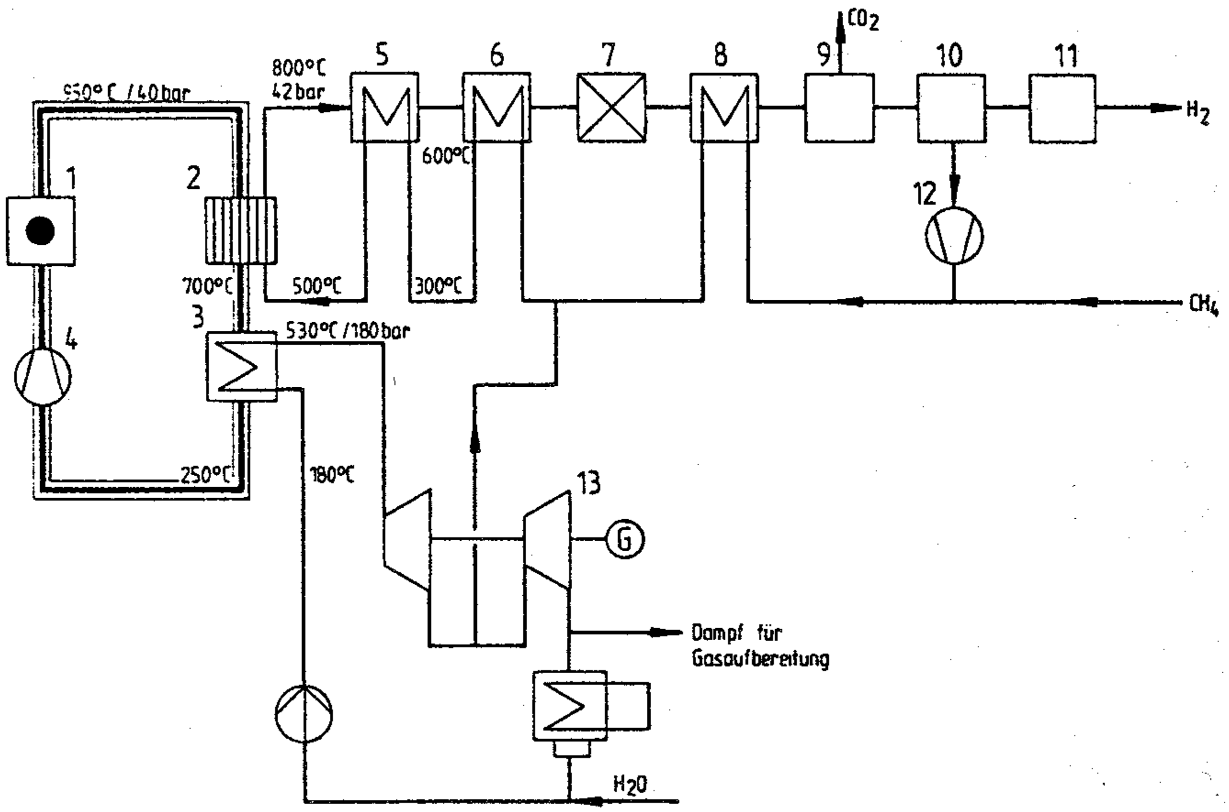

Figure B-5. Steam reforming of methane using nuclear heat flow sheet. The various components are: 1 – HTR; 2 – steam reformer; 3 – steam generator; 4 – He-blower; 5 – preheater gas; 6 – preheater gas; 7 – shift-conversion; 8 – CH_4–pre-heater; 9 – CO_2–washer; 10 – H_2/CH_4–separation; 11– methanation; 12 – CH_4 –compressor; 13 – steam turbine plant.

A demonstration test should be carried out of hydrogen production with nuclear heat through steam reforming. This would verify the capability to absorb thermal disturbances by separation of the kinetic characteristics between the heat application system and the reactor. The test would also demonstrate changes in plant output due to start-up, shutdown, and other load transients. Some component tests for demonstration or prototype are also necessary.

Nuclear steam reforming is the most straightforward strategy to demonstrate nuclear hydrogen generation in industrial scale within the next decade. The yield from natural gas will be enhanced 30–40% by using a technique that is currently deployed on a large scale. Steam reforming of methane to obtain hydrogen will remain the most economic, as long as natural gas availability continues at attractive prices.

R&D Issues for Deployment of Nuclear Systems in Refineries, Petrochemical Plants, and Aluminum Production

Huge amounts of process heat are currently consumed in crude oil refineries, petrochemical plants, and other industrial processes such as aluminum production. These applications have been identified as very promising for Generation IV concepts within the coming decades. Most will make use of the basic developments for associated systems such as the IHX, valves, hot gas ducts, and other components.

Table B-1 shows the typical thermal power demand in a 6 million-t/y crude oil refinery. It can be seen that most of the heat is consumed at a temperature below 540°C, which can be delivered by high quality steam. The hydrogen demands are comparably small, but will steadily increase depending on the crude oil grades. A high temperature reactor with IHX steam reformers and combined cycle could easily provide all necessary process energy for large refinery complexes.

Table B-1. Thermal power demand of a refinery (6 million t/y).

Process	Heat (MW)	Temperature (°C)	Pressure (bar)
Crude Oil Distillation	117	230-370	1
Vacuum Distillation	46	230-385	30 torr
Propane Deasphalting	53	50-80	35
Vacuum Residue Distillation	20	340-385	100
Vacuum Gas Oil Desulphurisation	17	340-385	40
Middle Dist. Desulphurisation	15	340-385	25
Gasoline Desulphurisation	12	340-385	30
Gasoline Reformer	53	430-540	30
Hydrogen Generation	5	820-850	30
Effluent Water Cleaning	3	20-60	1
Steam Generation	112	20-500	20
Total power demand	453		

A detailed design for a refinery served by high temperature nuclear heat could increase the efficiency and significantly decrease the CO_2 emissions related to the refining process. In addition, refineries are often combined with petrochemical plants for other products such as naphtha. The total installed world naphtha processing capacity is about 92,700,000 t/y. The total heat and electricity required to process 1.5 million t/y Naphtha is about 234 MW_{th}. The maximum temperature to crack naphtha into ethylene, propylene, and similar products is approximately 840°C. These requirements could be met by a temperature reactor system.

Necessary development to address these opportunities should address:

- Primary He–Secondary He Heat Exchanger (950–900°C, 300–250°C)
- Secondary He–Steam Cracker (900–800°C, 840–600°C)
- Secondary He–Super Heater (800–290°C, 600–250°C)
- Secondary He–Naphtha Evaporator (290–200°C, 250–120°C).

The heating of the naphtha with helium from 600–840°C in a fraction of a second has been theoretically been checked and appears to be feasible.

System optimization for a combined energy supply system of petrochemical plant and a refinery should be done together with process engineering companies and potential users. A development of specific components as mentioned above has to follow.

Another important industrial production is aluminum oxide production. Currently bauxite being the raw material is being transported over large distances to the places that offer cheap process heat. Afterwards, the aluminum oxide is transported again to the sites that offer cheap electricity to produce metallic aluminum by electrolysis. Typical of this is the aluminum producers in the Northwest in the U.S. that can take advantage of relatively inexpensive electricity from the hydroelectric plants of the Bonneville Power Authority. The total installed world aluminum production capacity (2001) is 56,326,000 t/y. In 1990 it was only approximately 40 million t/y. This represents an increase by about 40% in the last decade. Heat and electricity required for 300,000 t/y is approximately 400 MW_{th}. There are about 55 plants worldwide with production capacity over 300,000 t/y. The maximum temperature required for the process is about 950°C. However, reliability is essential, since smelters which are not kept at operational temperature can no longer be used and must be replaced.

The heat exchanger development required address these opportunities are:

- Primary He–Secondary He Heat Exchanger (only Primary Component)
- Secondary He (900–680°C)–Fluidized Powder Heat Exchanger (850–190°C)
- Secondary He (680–419°C)–Steam Generator (500–170°C)
- Secondary He (419–250°C)–Liquid Salt Heat Exchanger (400–240°C).

This application should also be taken into consideration by optimization of the adaptation of high temperature reactor concepts.

These examples show that near-to-medium term applications beyond dedicated electricity generation already exist for high temperature reactors. Specific components have to be developed for each process individually, but can profit from existing process engineering experience. The nuclear heat supply system, the IHX, and the isolation valves could be largely standardized. These applications require small to medium-sized reactors of 200 to 300 MW_{th} per module) with high reliability. Supply of this process heat by Generation IV concepts will enhance yields and significantly reduce CO_2 emissions.